MODELING AND STATIC AND MODAL ANALYSIS OF FUSELAGE BOMBARDIER CRJ 200 AIRCRAFT USING VARIOUS MATERIALS.

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ABSTRACT
This study details the low-speed configuration development process of the CRJ-700, focussing on half-model high Reynolds number wind tunnel tests. The procedure included flight testing, wind tunnel testing, and CFD design and analysis. A 7% scale half-model was used for the experimental development of the flaps and slats in the IAR 5 x 5 ft High Reynolds Number wind tunnel.
Decisions taken in the wind tunnel result in a brief and successful flight test program, and the results of these tests correlate extremely well with the data from the flight tests.
Keywords: wind tunnel tests, slats, flaps, and high lift.

I. INTRODUCTION

Bombardier Aerospace has developed and manufactured many business and regional aircraft within the last ten years. A 70-seat variant of the wildly popular Canadair Regional Jet CRJ-200 is called the CRJ-700. With a totally novel planform and cutting edge equipment, the CRJ-700 wing was virtually a blank sheet design. The CRJ-700 aerodynamic design was developed with great consideration for the airplane's low-speed characteristics. The design was driven by three factors: performance, simplicity, and safety. In actuality, safety necessitated stall features that could be easily recognised, such as a nose down pitching moment and minimal to no roll excursion. Double-slotted hinged flaps, like to the CRJ-200's, were used for ease of usage. Performance was defined as having strong second-segment climb capabilities and as much useable lift as feasible.

II. AIRCRAFT DESIGN CHARACTERISTICS

At Mach number 0.78, the CRJ-700 was intended to transport 70 passengers and 3 crew members over a distance of 1685 nautical miles (1985 NM for the extended range variant).
The maximum cruising altitude is 41,000 feet, and the maximum operational Mach number is 0.83. The aircraft, which has a Maximum Take-Off Weight (MTOW) of 73,000 pounds (or 75,250 pounds for the extended range variant), is propelled by two General Electric CF-34-8C1 turbofans installed in the fuselage, each of which can provide 12,670 pounds of thrust.
At a maximum landing weight of 67,000 pounds, the landing distance is 4850 feet, while the takeoff distance is 5,130 feet at MTOW. The aircraft's overall layout is shown in Figure 1.

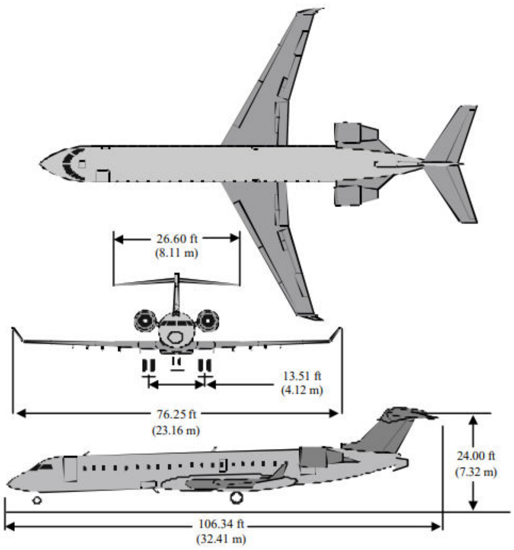

Figure 1: CRJ-700 aircraft general arrangement.

III. CRJ-700 HIGH LIFT WING DESIGN

3.1 Planform Design

The CRJ-700 initial wing planform W30 was obtained from the CRJ-200 wing by adding a 72" root plug and extending the leading edge by 9% chord (Figure 2). The intention was to maintain the existing wing box structure on the outer wing panel and limit airfoil modifications to the part of the wing forward of the front spar.

This planform was abandoned after it was realized that the resulting wing sections could not provide adequate high-lift characteristics. The leading edge crank was also an impediment to the installation of a simple leading edge device. A new planform, W33, was designed, with the 72" root plug but this time with a straight leading edge. The constraint of preserving the CRJ-200 front spar was also removed and new advanced supercritical wing sections were designed. The wing retained the simple double-slotted hinged flaps in two segments of the CRJ-200 and was fitted with new leading edge slats. After the first series of high speed and low speed tests, the W33 wing was replaced by wing W34, with the same planform and improved wing sections. Flaps and slats were redesigned to accommodate the new wing geometry.

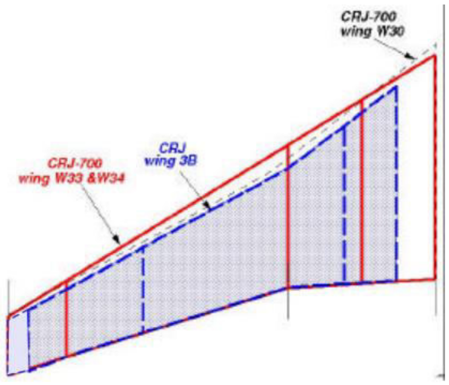

Figure 2: CRJ-700 wing planform development

The reference area of wing W34 is 738 ft2 and its aspect ratio 7.38. The quarter chord sweep of the outboard wing panel is 26.9 degrees. The wing is fitted with winglets canted 20 degrees.

3.2 High Lift System Design

Figure 3 shows the planform definition of the CRJ-700 high-lift system. The trailing edge flaps are double-slotted hinged flaps. The inboard flap has a constant 33-inch chord and is fitted with a spring-loaded constant chord flap vane. The outboard flap is physically the same as the outboard flap of the CRJ-200. The flap chord is a constant percentage of the main wing chord (24% chord). It is fitted with a fixed tapered flap vane. The inboard flap deflection angles are 10 and 20 degrees for take-off, 30 degrees for approach and 45 degrees for landing. The outboard flap is geared with a ratio 8/9 to the inboard flap deflections, deploying therefore to 40 degrees in landing. The gearing improves the spanwise load and preserves excellent aileron performance in all configurations. The leading edge slats cover the full span except for an inboard segment of the wing, which was left unprotected to improve the stall characteristics. The slats are tapered, covering 15% of the wing chord at the break and 17% chord at the wing tip. The slat deflections are 20 degrees for 0 and 10 degrees flap settings and 25 degrees for all other flap settings.

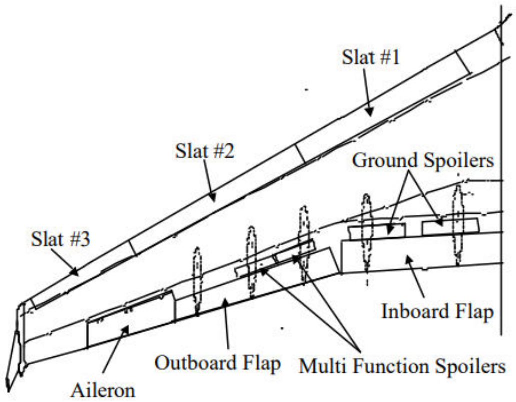

Figure 3: CRJ-700 flaps and slats planform definition

Two pairs of multifunction spoilers supplement the ailerons and two pairs of ground spoilers complete the set of wing movable surfaces. The trailing edge flaps of the CRJ-700 retain the simplicity of the CRJ-200 design. Figure 4 shows various settings of the inboard flap. The flap rotates around a fixed hinge axis to 45 degrees. A small vane is nested against the flap leading edge in the flap-retracted position and springs into position as the flap is deployed. The vane on the outboard flap (Figure 5) is fixed to the flap. This outboard flap rotates to 40 degrees, in a geared ratio to the inboard flap setting. A bent up trailing edge (BUTE) door improves the flow in the cove region on the outboard flap. At flap deflections below 20 degrees, the BUTE door effectively seals the passage to the upper surface of the vane, allowing the flap to operate as a single-slotted flap. This improves the lift to drag ratio of the take-off configuration.

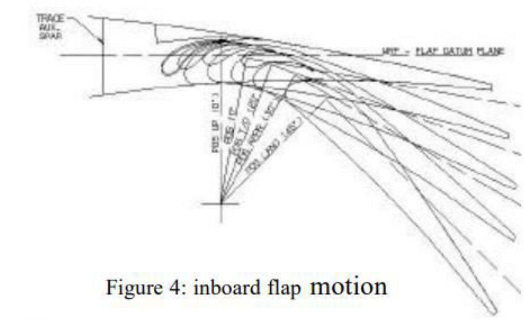

Figure 4: inboard flap motion

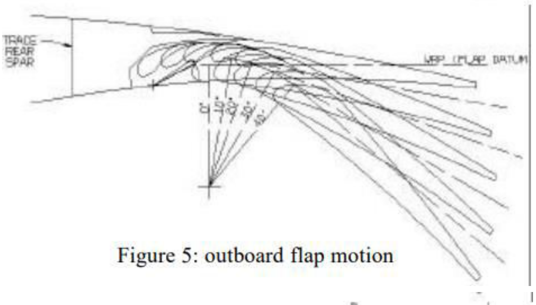

Figure 5: outboard flap motion

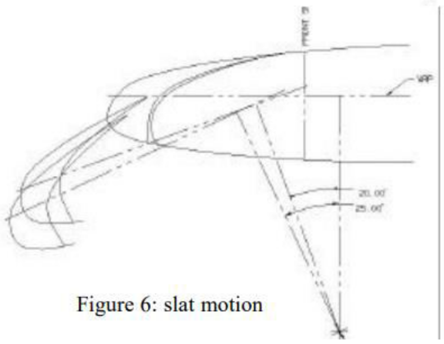

Figure 6: slat motion

Figure 6 illustrates the slat settings. For simplicity, the slats are deployed along a circular arc track with three positions: retracted, 20 degrees for normal take-off and 25 degrees for short take-off, approach and landing.

IV. THEORETICAL METHODS

At the early stages, the development of the highlift systems was conducted using Computational Fluid Dynamics (CFD) methods: three codes were used for the design of the multi-element airfoils. CEBECI, a viscous panel method with strong boundary layer coupling developed by T. Cebeci and his team at the University of California in Long Beach [1], was used for rapid evaluation of configurations. The MSES viscous Euler code of Drela [2] and the NSU2D 2D unstructured grid Navier-Stokes code developed by D. Mavriplis [3] were used for the design and final verification of flaps and slats.

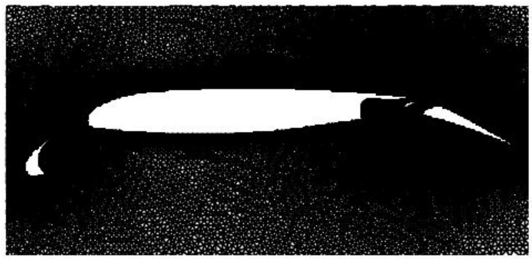

Figure 7: NSU2D unstructured Navier-Stokes grid for a CRJ-700 multi-element airfoil.

V. WIND TUNNEL TESTING

The CFD design was further optimized in the wind tunnel. The low speed wind tunnel tests were conducted in three phases: - Initial development wind tunnel tests to validate CFD designs and to obtain initial performance figures. These tests used the early wing configuration W33.

- Detailed design and development wind tunnel tests leading to the aerodynamic freeze of the external lines. These tests used the final wing configuration W34.

- Production wind tunnel tests to verify in detail many aircraft possible configurations and to obtain the data needed before the aircraft first flight. These tests used the production configuration of the aircraft. Two low-speed tests were conducted in each phase: a high-Reynolds number half-model test and a low Reynolds number full model test.

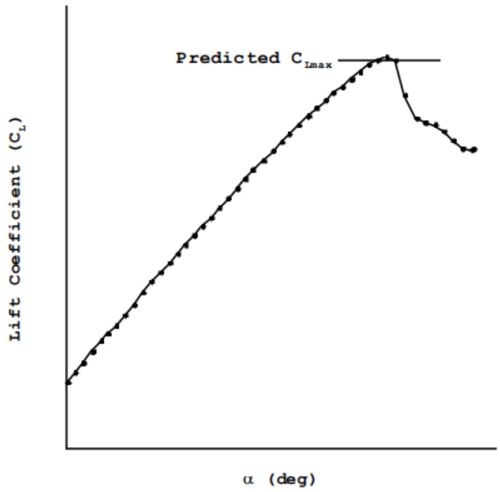

Figure 8: Comparison of wind tunnel data with theoretical prediction of CLmax for the CRJ-700 clean configuration at wind tunnel conditions: Mach 0.20, chord Reynolds number 6.5 million.

The first high-lift development test was conducted in January 1996 using a 7% scale half-model in the 5ft x 5ft wind tunnel of the Canadian Institute for Aerospace Research (IAR) in Ottawa. The objectives in this test were:

- To evaluate various flap and slat designs and establish optimal angles, gaps and overlaps;
- To determine the optimal location and geometry of the inboard slat inboard end;
- To measure CLmax and determine longitudinal stall characteristics;
- To investigate Mach number and Reynolds number effects;
- To measure the effectiveness of control surfaces in high-lift configurations at high Reynolds number.

Comparison with data obtained at lower Reynolds number in full model tests at the IAR 6ftx9ft atmospheric tunnel and at the MicroCraft 7ftx7ft high-speed tunnel in El Segundo, California, were used to estimate the half-model corrections.

The second high-lift development test was carried out in January 1997, using a configuration with the final wing W34. The objectives of the test were the same as those of the first phase, but with a view to freezing the high-lift systems. The test was also used to determine the final take-off and landing flap and slat settings, including alternate configurations and to establish the effect of various ice shapes on the wing and tailplane. Slat loads were measured using specially designed straingauged components.

5.1 Wind Tunnel Description

The IAR 5ft x 5ft tunnel is a blow-down facility, shown schematically in Figure 11, which can be used to test in the subsonic, transonic and supersonic flow regimes.

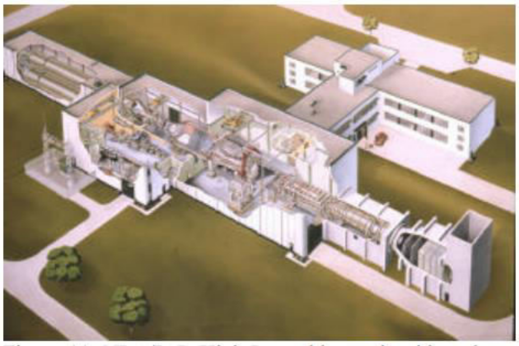

Figure 9: NRC/IAR High Reynolds number blow-down tunnel

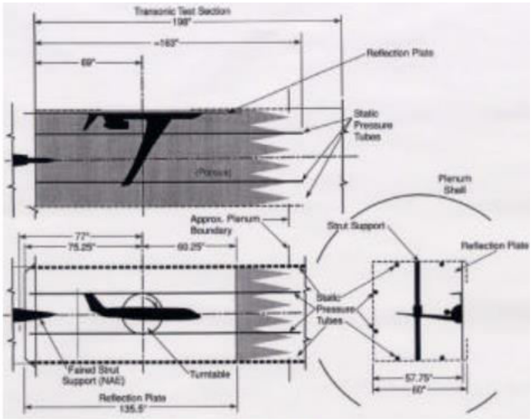

Figure 10: Wind tunnel half-model test section

5.2 Model Description

The model was a 7% scale representation of the starboard half of the CRJ-700 aircraft, as shown in Figure 13. The reflection plane model was mounted to the tunnel sidewall balance through the use of an L-shaped bracket. A 1-inch thick boundary layer plate, identical in plan view to the perimeter of the aircraft plane of symmetry, isolated the model from the wall. There was a 0.1-inch spacing between the model plate and the boundary layer plate. A triple labyrinth seal on the outboard face of the boundary layer plate prevented dynamic pressure build up between the model plate and the boundary layer plate. A single electric contact was installed to indicate any labyrinth fouling under load.

Figure 11: 7 percent scale half-model of the CRJ-700 installed in the IAR 5-ft high Reynolds number wind tunnel

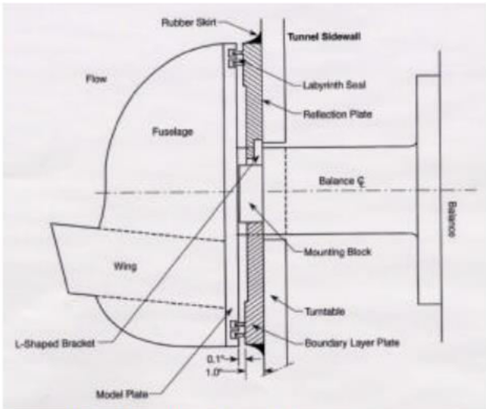

Figure 12: Schematic of the model mounting arrangement

5.3 Test Procedures

Bombardier used this high Reynolds number facility for high-lift systems development for the first time during the Global-Express business jet project. Procedures leading to valid and repeatable forces, moments and pressure measurements were established then. The main challenge was to obtain stabilized flow qualities during a period sufficiently long to traverse the large range of angles of incidence required for high-lift experiments. Most of the CRJ-700 runs were performed at a nominal Mach number of 0.20 and a Reynolds number of 8.40 million per foot or 6.5 million based on the model reference chord. Additional runs were made at Mach 0.15, 0.30 and 0.40 to investigate Mach number effects. At Mach 0.20, runs were also made at three additional Reynolds numbers: 4.7, 7.3 and 10 million per foot to investigate scale effects. The model was pitched through a range of angles of incidence between –6 degrees and 25 degrees for non-slatted configurations and between –6 degrees and 30 degrees for configurations with deployed slats. A few runs were made during which the model was pitched to 33.5 degrees. After examination of the repeatability of force and pressure data obtained with fixed pitch, pitch pause and continuous sweep runs, subsequent runs were made with continuous pitch motion at the slowest sweep rate compatible with available stable flow conditions. This time varied between 15 and 30 seconds, depending on the Mach number and Reynolds number selected [6]. The electronically collected data was filtered at 3 Hertz then digitized at 100 samples per second. The aerodynamic data was corrected for wind tunnel wall interference using the wall pressure signature. The correction was based on a procedure developed for half-models by Mokry [7]. The procedure uses the model geometry, the cross-sectional area distribution and the tunnel parameters. It yields corrections DM to the freestream Mach number, Da to the model angle of incidence and DCDbuyancy to the drag. Corrections for the tunnel freestream flow angularity were applied to the data using precalibrated correction algorithms. All high Reynolds number high-lift runs were performed transition-free on the wing. Transition was fixed on all other surfaces using polyester-resin cylinders. A selected number of flow visualization runs were performed using the fluorescent mini-tuft technique. Repeatability on maximum lift coefficient was DCLmax = 0.01 to 0.02 and the scatter on astall was negligible. Repeatability on the drag of high lift configurations was DCD = 20 to 30 drag counts. Measurements of pitching moments were repeatable within DCM = 0.01. With these values, the IAR 5-ft tunnel test was considered adequate for the validation of flaps and slats geometry and kinematics and the prediction of CLmax and global longitudinal stall characteristics. To predict tailplane angles to trim and the drag polars of take-off and landing configurations, it was necessary to resort to data from a 7% scale full model test performed at the IAR 6ftx9ft wind tunnel (Figure 15).

Figure 13: 7% scale full model of the CRJ-700 in IAR 6ftx 9ft atmospheric wind tunnel

VI. FLIGHT TESTING

The CRJ-700 aircraft first flew on May 27, 1999 (Figure 20). The aircraft obtained Transport Canada certification on December 22, 2000. The aircraft obtained subsequently European JAA certification in January 2001 and the American FAA certified the airplane in February 2001. The aircraft entered revenue passenger service on February 2001. The highlift configuration was ultimately validated during an extensive flight test program.

Figure 14: The CRJ-700 prototype aircraft #10001 on its maiden flight.

The aircraft is fitted with a stall protection system including a stick shaker for stall warning and a stick pusher for stall recovery. The stick pusher activates ahead of natural stall for the clean configuration and post-natural stall for all configurations with the slats deployed. Handling stall tests demonstrated compliance with all stall characteristics requirements. These included straight and turning stalls at 1 kt/sec deceleration, with power on and off, with spoilers retracted and extended and with and without lateral center of gravity imbalance. Dynamic stall entries at 3 kt/sec were also demonstrated. Figure 21 shows lift curves from the IAR 5-ft wind tunnel test, trimmed for the most forward centre of gravity, compared to equivalent data from performance flight tests. This figure shows good correlation for all flap angles. For take-off configurations requiring good climb gradient, a slat angle of 20 degrees was finally selected.

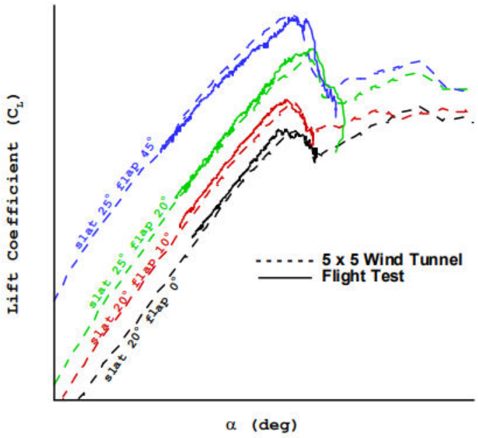

Figure 15: Comparison of trimmed lift curves from the IAR 5-ft wind tunnel test with flight test data.

VII. CONCLUSIONS

Using CFD techniques, the CRJ-700 flaps and slats' geometry and deployment schedule were created. Low speed wind tunnel studies using a complete model at low Reynolds number and a half-model at high Reynolds number confirmed the expected characteristics of the aircraft. With the exception of the pitching moments, there was a strong correlation between the two models' findings. Therefore, tailplane angles for trim and drag of high-lift designs were extracted from full-model experiments and scaled appropriately. Flight test data showed that reliable estimations of the aircraft characteristics, including CLmax, could be obtained from half-model tests conducted in the IAR 5 x 5 ft wind tunnel at 6.5 million chord Reynolds number. A similar decision was made about the Global Express before.

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